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Terrestrial Geophysics in the SeaRISE Project

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Radar Sounding

Radar sounding serves multiple purposes. The most general and obvious is mapping ice thickness and the surface and bedrock topography of the ice sheet. Determining the surface and basal elevations of the ice sheet requires determining the height of the sounding aircraft, although measuring ice thickness does not. In addition to this basic mapping, there are many problem-oriented uses of radar sounding. Specific applications to the problems of the grounded and floating parts of the West Antarctic ice sheet are as follows.

1) Examination of the variations in bottom echo strength as a means of distinguishing between wet and frozen beds and perhaps locating ponded water beneath the inland ice.
2) Mapping ice rises, ice rumples, and ice rafts on the ice shelves. Ice rises and ice rafts are characterized by a lack of "clutter", that is, scattering on the radar return from crevasses buried beneath the surface. Ice rumples do have clutter, as do the ice streams and portions of the ice shelf that have arisen from the ice streams.
3) Mapping the boundaries of ice streams, and zones in the inland ice that are incipient ice streams, by the location of clutter zones. The work to date has shown very complex patterns of cluttered and clutter-free ice around the heads of the West Antarctic ice streams.
4) Mapping of "debris tracks", and identification of their sources. "Debris

tracks" are internal reflectors arising from either rock debris or bottom crevasses that can be associated with a particular geographical location as a source, and then traced downstream. The divergence between debris tracks and the present day flow lines acts as a record of changing flow patterns.

5) Measurements, with short pulse radar systems on the ground, of the depth to buried crevasses as a means of determining how long it has been since those crevasses were open at the surface. In the case of ice stream C, such measurements have provided an estimate of how long ago it was that ice stream C ceased to be active.

6) Profiling of internal layers for analysis in terms of changing configuration of the ice sheet, as was done for the vicinity of Byrd Station.

7) Local radar mapping in association with strain and gravity measurements. In the case of strain measurements, thickness variations need to be known to provide adequate interpretation of the strain rates. In the case of gravity measurements, radar surveys are needed to provide the subglacial topographic corrections necessary for the determination of regional characteristics.

8) Measurement of anisotropy in the ice through its effect on radio wave polarizations. Particular attention in this regard should be paid to the depolarization of internal reflections that can yield clues to variation of crystal fabric with depth.

9) Mapping the radar diffraction pattern on a survey grid to be compared with later remapping to see how the diffraction pattern has changed

relative to the surface. Comparison with satellite-determined velocities should reveal whether the diffraction pattern is fixed relative to a stationary bedrock, relative to the base of the ice, or relative to reflection horizons deep within the ice above the bedrock. This is a point of great interest in determining the contributions of bed deformation and strain within the ice and to the total ice movement.

10) Determination of the small-scale statistical roughness of the basal reflecting surfaces can provide useful information about basal sliding. A digital radar recording system makes it possible to determine such statistical characteristics. We hope that when detailed comparisons are made between the characteristics of zones where there is a basal deforming till and zones where there is not, it may become possible to determine the presence of a deforming layer by means of analyses of airborne radar along.

Seismic Shooting

The purpose of seismic shooting, in addition to water depth measurements on floating ice, is to provide information about the internal physical characteristics of the ice sheet, the rock beneath it, and the interface between the two. The point of greatest interest in the current measurements is the extent and nature of a deforming layer immediately below the ice, observed by seismic measurements to be a zone of high porosity and high hydrologic pore pressure. Seismic anisotropy is also of interest because of the relatively large effect of crystal orientation on seismic wave speeds, and because of the importance of crystal orientation in ice flow.

High-resolution seismic reflection profiles utilize both compressional and shear waves to yield the details of the subglacial material and the ice-rock interface. If a subglacial layer is sufficiently thick (more than 5 m), seismic travel times can be used to calculate both its porosity and pore-water pressure. Additionally, studies of the amplitudes of compressional waves that are converted to shear waves upon reflection at the base of the ice may prove useful for detecting a millimeters-thick basal water layer. The comparison of seismic reflection times with radar reflection times at a large number of stations should give a clue to anisotropy in the ice, since seismic velocities are markedly affected by anisotropy whereas electromagnetic wave velocities are not. But the principal way of determining anisotropy is through wide-angle reflection sounding, by means of which the wave velocity can be determined at different angles of incidence and along different azimuths.

Short refraction shooting yields detailed determinations of the wave velocities as a function of depth in the firn layers. Experience has shown that the correlation between wave velocity and density is excellent. The "critical depth of densification" and the depth of the firn-ice boundary can be found by analysis of the wave-velocity gradient as a function of depth. In addition, long-term mean accumulation rates can be estimated from the seismic data, particularly where horizontal strain rates have been determined.

Seismic long-refraction and deeply penetrating reflection shooting, while aimed primarily at the geological objective of determining the upper crustal structure beneath the ice, serve a glaciological purpose as well in yielding information about the stratigraphy, age, and thickness of subglacial sediment, hence about the glacial history of the region. Subglacial layers that are

probably composed of Cenozoic marine sediments and whose aggregate thickness may be a kilometer or more are found extensively in West Antarctica.

Passive Seismic Studies

Passive seismic monitoring of microearthquakes can be used to study brittle fracture within the ice or the rock beneath it. Common parameters available from these studies are fault location, orientation, and displacement, as well as the size of the rupture area, stress drop, and energy released. The parameters derived from microearthquakes originating in the chaotic zones that bound the active ice streams should increase our understanding of the stress regime in these regions as well as the contribution of brittle fracture to the observed strain rates. Similarly, parameterization of seismic events arising from the base of the active ice streams may give insight into the erosional processes that are critical to the mass balance of any deforming sediments. In one relatively inactive region at least (ice stream C) faulting may contribute substantially to ice motion.

Electrical Resistivity

There is a large contrast in electrical resistivity between ice or permafrost on the one hand and liquid water or wet rock on the other. Thus, electrical resistivity profiles have the potential capability of revealing the depth to the melting point, whether that melting point is found at the base of the ice or in the subglacial rock.

Extensive studies on the Ross Ice Shelf have suggested that a deep layer with electrical resistivity much higher than in the overlying ice exists at or

near the bottom of ice streams and outlet glaciers. If this is so, it is possible that it arises from annealing of the ice due to its strain history. Other increases in electrical resistivity with depth may be associated with the Wisconsin-Holocene Boundary. If the latter association can be confirmed, it will then be possible to estimate the depth to that boundary from resistivity measurements.

Gravity

Gravity anomalies, particularly combined with seismic measurements, are an effective tool for determining deeper crustal structure. Anomalies averaged over extensive areas are useful also for their potential to reveal isostatic imbalance, which is a measure of average glacial change over the last several thousand years. Older studies of this kind in West Antarctica suffered from the large errors in free-air gravity anomalies that stem from poorly known elevations of the surface stations. Satellite determinations of elevation reduce those errors by at least an order of magnitude. In fact, modern navigational techniques will soon make it possible to conduct gravity surveys by small aircraft in West Antarctica.